Zackenberg basic

the climatebasis and geobasis programme

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2 Zackenberg Basic

The ClimateBasis and GeoBasis programmes

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GeoBasis and ClimateBasis provide long-term data of climate, hydrology and physical landscape variables describing the environment at Zackenberg. This include climatic measurements, seasonal and spatial variations in snow cover and local microclimate in the Zackenberg area, the water balance of the river Zackenberg drainage basin, the sediment and solute transport of the river Zackenberg, the carbon dioxide (CO_2) and methane (CH_4) fluxes from a well-drained heath area and a fen area, the seasonal development of the active layer, temperature conditions and soil water chemistry of the active layer, and the dynamics of selected coastal and periglacial landscape elements. For a map of the main study sites, see figure 2.1.

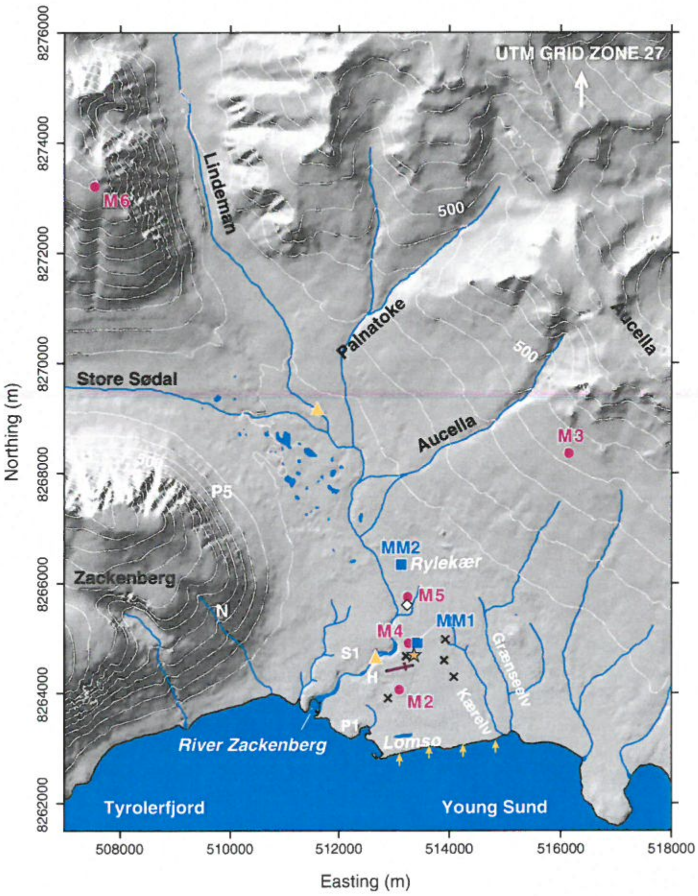


Figure 2.1 GeoBasis and ClimateBasis plots. Asterix=Meteorological station. H=Hydrometric station. Rectangles=Eddy towers. Circles=Snow and micrometeorological stations. Triangles= Water sample sites. N=Nansenblokken (photo site). Crosses=Soil water sites. Square=Methane site. Arrows= Coastal cliff recession.

GeoBasis is operated by Department of Bioscience, Aarhus University, in collaboration with Department of Geography and Geology, University of Copenhagen. In 2011, GeoBasis was funded by Danish Ministry of Climate, Energy and Building as part of the environmental support programme DANCEA – Danish Cooperation for Environment in the Arctic. ClimateBasis is run by Asiaq - Greenland Survey who operates and maintains the meteorological station and the hydrometric station. ClimateBasis is funded by the Government of Greenland.

More details about sampling procedures, instrumentation, locations and installations are given in the GeoBasis manual and the ClimateBasis manual. Both can be downloaded from www.zackenberg.dk. Selected validated data from the monitoring programmes are also accessible from this website. For other validated GeoBasis data – please contact Charlotte Sigsgaard (cs@geo.ku.dk), Maria Rask Pedersen (mrp@geo.ku.dk) or programme manager Mikkel P. Tamstorf (mpt@dmu.dk). For matters concerning the ClimateBasis programme and data please contact programme manager Kisser Thorsøe (kit@asiaq.gl).

2.1 Meteorological data

The meteorological station at Zackenberg was installed during summer 1995. Technical specifications of the station are described in Meltofte and Thing 1996. Once a year the sensors are calibrated and checked by Asiaq - Greenland Survey. The problem with the malfunctioning satellite modem on the eastern mast was solved during the annual technical visit in August 2011 and data are again sent to Asiaq on a daily basis.

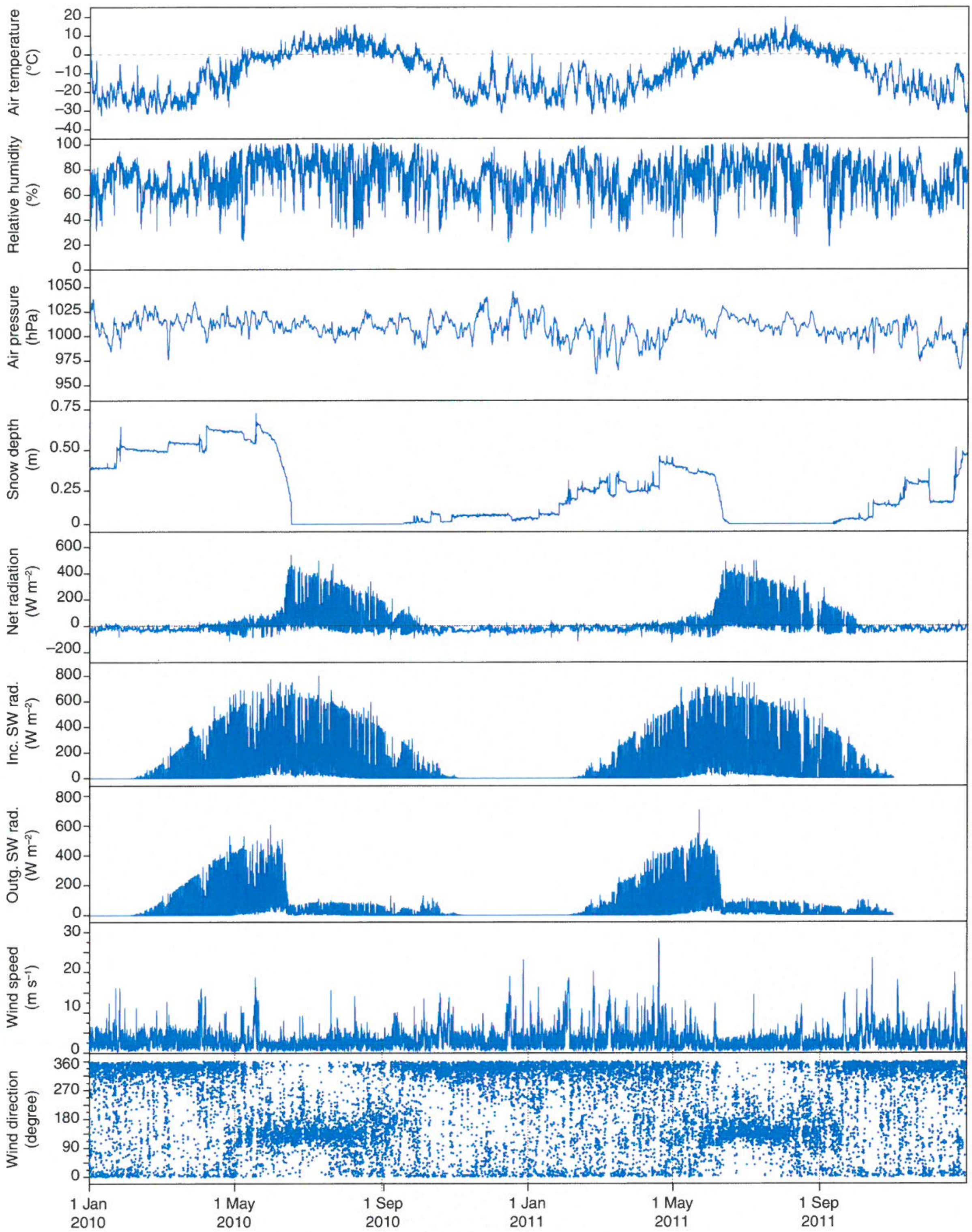


Figure 2.2 Variation of selected climate parameters during 2010 and 2011. Wind speed and direction are measured 7.5 m above terrain; the remaining parameters are measured 2 m above terrain. Data from November and December 2011 are preliminary. Outgoing and incoming SW radiation is not available.

Data was collected from the climate stations 1 November 2011, just before the research station was closed for the winter. As data for the last two month of 2011 has not been retrieved from both stations yet, a thorough presentation of data from 2011 will be presented in the 2012 annual report. Data for 2010 and 2011 are shown in

*Table 2.1 Monthly mean values of climate parameters 2010 and 2011. *Data for 2011 are preliminary.*

Year	Month	Air temperature (°C)		Rel. humidity (%)	Air press. (hPa)	Net rad. ($W m^{-2}$)	Shortwave rad. ($W m^{-2}$)		Wind velocity ($m s^{-1}$)		Dominant wind dir.
		2.0 m[1)]	7.5 m				In	Out	2.0 m	7.5 m	7.5 m
2010	Jan	−20.3	−18.8	71	1007.9	−18	0	0	2.7	3.2	NNW
2010	Feb	−23.5	−21.5	69	1019.4	−26	6	5	2.4	3.0	NNW
2010	Mar	−23.9	−22.0	65	1015.3	−26	67	51	2.5	3.1	NNW
2010	Apr	−12.7	−11.6	72	1012.7	−15	156	126	2.8	3.5	NNW
2010	May	−2.8	−2.2	80	1016.5	1	236	177	2.9	3.5	SE
2010	Jun	1.9	2.1	85	1011.1	98	272	95	1.7	2.0	SE
2010	Jul	5.3	5.4	80	1004.8	123	264	40	2.2	2.6	SE
2010	Aug	5.3	5.9	74	1010.3	58	164	27	2.0	2.6	SE
2010	Sep	−0.6	0.2	80	1011.2	3	61	11	2.0	3.0	NNW
2010	Oct	−9.0	−7.8	70	1010.0	−28	14	9	3.2	4.5	NNW
2010	Nov	−20.5	−18.6	68	1013.7	−33	0	0	2.0	2.8	NNW
2010	Dec	−16.7	−15.1	65	1015.9	−33	0	0	2.8	3.9	NNW
2011	Jan	−20.2	−18.6	68	1009.2	−24	0	0	2.6	3.5	NNW
2011	Feb	−14.4	−13.1	80	998.7	−16	6	5	3.3	4.4	NNW
2011	Mar	−19.2	−17.7	64	998.7	−26	58	47	2.9	3.9	NNW
2011	Apr	−12.7	−11.9	73	995.2	−12	140	118	3.2	4.2	NNW
2011	May	−4.0	−3.1	75	1015.0	−2	254	199	2.1	2.8	NNW
2011	Jun	2.3	2.8	78	1017.0	122	300	84	1.6	2.1	SE
2011	Jul	5.8	6.1	80	1009.9	118	254	41	1.8	2.4	SE
2011	Aug	5.6	–	79	1012.2	61	147	23	2.0	2.7	SE
2011	Sep	−0.8	–	72	1002.2	2	87	14	2.0	2.8	NNW
2011	Oct	−10.2	–	71	1005.2	−23	14	10	3.7	5.0	NNW
2011*	Nov	−16.6	–	72	1000.6	−21	–	–	2.7	3.7	NNW
2011*	Dec	−19.0	–	70	995.0	−22	–	–	3.0	4.0	NNW

figure 2.2 and monthly mean values of climate parameters for 2010-2011 are shown in table 2.1. Furthermore, annual values for selected parameters for 1996 to 2010 and mean wind statistics have been updated in tables 2.2 and 2.3.

2011 was a normal year for most climatic parameters (figure 2.2), but February mean air temperature was relative high compared to previous year (figure 2.3). The first positive temperatures in 2011 were measured 28 April and by 24 June the temperature for the first time exceeded 10 °C. The maximum temperature was 19.7 °C (1 August). Monthly mean values of selected climate parameters for June, July and August from 1996-2011 are shown in table 2.4. The sum of positive degree-days during 2011 was a little below the average for the last 15 years (table 2.5). Episodes of night frost were registered in both July and August but the first negative diurnal mean temperature was not measured until 4 September.

2.2 Climate gradients, snow, ice and permafrost

In order to increase the spatial resolution of meteorological data and to describe the gradients (both altitudinal and coast/inland), several smaller automatic weather stations have been installed in the area. In 2003, the station M2 was installed in the Zackenberg valley and the station M3 was installed halfway up Aucellabjerg (Rasch and Caning 2004). M6 was installed at the top of Dombjerg in 2006 (Klitgaard et al. 2007) and M7 was installed in 2008 in the area just west of Store Sø in Store Sødal (Jensen and Rasch 2009). Three automatic weather stations were installed on the A.P. Olsen Glacier and data from these are reported in Chapter 3.

Monthly mean temperatures from the four weather stations are shown in figure 2.4. Here it is very clear that the lower lying stations have larger annual variations than the higher lying stations. Especially

*Table 2.2 Annual mean, maximum and minimum values of climate parameters for 1996 to 2011. *Data for 2011 are preliminary.*

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011*
Annual mean values																
Air temperature, 2 m above terrain (°C)	−9.0	−10.1	−9.7	−9.5	−10.0	−9.7	−8.6	−9.2	−8.5	−7.7	−8.1	−8.7	−8.1	−9.4	−9.7	−8.6
Air temperature, 7.5 m above terrain (°C)	−8.4	−9.3	−9.1	−8.9	−9.4	−9.2	–	−8.7	−7.9	−6.9	−7.6	−8.2	−7.9	−8.6	−8.6	–
Relative air humidity, 2 m above terrain (%)	67	68	73	70	70	71	72	71	72	71	72	69	72	71	73	73
Air pressure (hPa)	1009	1007	1010	1006	1008	1009	1009	1008	1007	1008	1007	1006	1008	1010	1012	1005
Incoming shortwave radiation ($W m^{-2}$)	113	104	101	100	107	112	105	104	99	101	107	107	107	104	104	–
Outgoing shortwave radiation ($W m^{-2}$)	52	56	55	56	52	56	54	49	42	43	54	45	52	38	45	–
Net radiation ($W m^{-2}$)	16	9	6	4	14	13	–	8	–	–	10	13	8	13	9	13
Wind velocity, 2 m above terrain ($m s^{-1}$)	2.7	3.0	2.6	3.0	2.9	3.0	2.8	2.6	3.0	2.9	2.8	2.6	2.9	2.6	2.4	2.6
Wind velocity, 7.5 m above terrain ($m s^{-1}$)	3.1	3.4	3.2	3.7	3.3	3.4	3.3	3.1	3.6	3.5	3.4	3.2	3.5	3.2	3.1	3.5
Precipitation (mm w.eq.), total	223	307	255	161	176	236	174	263	253	254	171	178	202	169	–	–
Annual maximum values																
Air temperature, 2 m above terrain (°C)	16.6	21.3	13.8	15.2	19.1	12.6	14.9	16.7	19.1	21.8	22.9	16.4	18.4	17.3	16.1	19.7
Air temperature, 7.5 m above terrain (°C)	15.9	21.1	13.6	14.6	18.8	12.4	–	16.7	18.5	21.6	22.1	15.6	18.2	17.7	15.7	–
Relative air humidity, 2 m above terrain (%)	99	99	99	99	100	100	100	100	100	99	99	99	99	101	102	101
Air pressure (hPa)	1042	1035	1036	1035	1036	1043	1038	1038	1033	1038	1038	1037	1043	1034	1046	1031
Incoming shortwave radiation ($W m^{-2}$)	857	864	833	889	810	818	920	802	795	778	833	769	747	822	801	–
Outgoing shortwave radiation ($W m^{-2}$)	683	566	632	603	581	620	741	549	698	629	684	547	563	488	607	–
Net radiation ($W m^{-2}$)	609	634	556	471	627	602	–	580	–	–	538	469	565	548	539	496
Wind velocity, 2 m above terrain ($m s^{-1}$)	20.2	22.6	25.6	19.3	25.6	20.6	21.6	20.6	22.2	19.9	20.8	27.6	24.5	20.5	17	26.6
Wind velocity, 7.5 m above terrain ($m s^{-1}$)	23.1	26.2	29.5	22.0	23.5	25.0	25.4	23.3	25.6	22.0	22.8	29.6	28.9	24.4	23.2	30.1
Annual minimum values																
Air temperature, 2 m above terrain (°C)	−33.7	−36.2	−38.9	−36.3	−36.7	−35.1	−37.7	−34.0	−34.0	−29.4	−38.7	−33.9	−35.3	−33.9	−32.5	−31.9
Air temperature, 7.5 m above terrain (°C)	−31.9	−34.6	−37.1	−34.4	−34.1	−33.0	–	−32	−32.1	−27.9	−37.2	−32.5	−33.9	−33	−29.3	–
Relative air humidity, 2 m above terrain (%)	20	18	31	30	19	22	23	21	17	22	21	18	24	25	22	18
Air pressure (hPa)	956	953	975	961	969	972	955	967	955	967	968	969	963	967	976	961
Incoming shortwave radiation ($W m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–
Outgoing shortwave radiation ($W m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–
Net radiation ($W m^{-2}$)	−86	−165	−199	−100	−129	−124	–	−98	–	–	−99	−99	−104	−146	−119	−127
Wind velocity, 2 m above terrain ($m s^{-1}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind velocity, 7.5 m above terrain ($m s^{-1}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

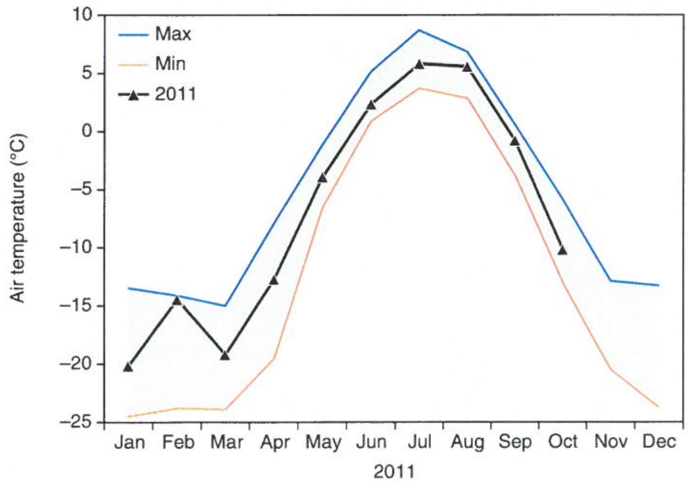
Table 2.3 Mean wind statistics are based on wind velocity and direction measured 7.5 m above terrain in 1997, 1998, 2000 and 2002-2009. Due to re-evaluation of the figures for 2003, differences can be seen if compared to earlier publications. Calm is defined as wind speed lower than 0.5 m s⁻¹. Max speed is maximum of 10 minutes mean values. Mean of maxes is the mean of the yearly maximums. The frequency for each direction is given as percent of the time for which data exist. Missing data amounts to less than 8 % of data for the entire year.

Year	Mean[1)]				2010			2011*		
Direction	Frequency	Velocity (m s^{-1})			Frequency	Velocity (m s^{-1})		Frequency	Velocity (m s^{-1})	
	%	mean	mean of max	max	%	mean	max	%	mean	max
N	15.8	4.5	24.2	29.6	14.3	3.9	23.2	13.6	5.0	29.7
NNE	3.6	2.7	18.6	28.9	3.5	2.1	15.0	3.5	2.8	14.9
NE	2.5	2.3	15.3	23.2	2.4	2.0	15.0	2.3	2.2	16
ENE	2.7	2.4	13.1	17.4	2.7	2.0	10.1	2.6	2.4	16.4
E	3.9	2.0	8.9	10.7	3.6	2.0	7.1	3.7	2.1	6.9
ESE	6.7	2.2	8.9	10.3	6.7	2.3	6.9	6.9	2.3	7.2
SE	8.7	2.4	9.6	18.1	9.9	2.6	7.9	10.6	2.5	7.5
SSE	5.8	2.4	9.4	16.2	5.8	2.5	9.6	6.3	2.4	7.3
S	4.1	2.5	8.1	9.9	4.1	2.3	6.9	4.4	2.5	7.6
SSW	3.0	2.3	8.5	13.4	2.8	2.1	8.3	2.8	2.1	7.4
SW	2.6	2.1	8.0	12.2	2.4	1.9	5.4	2.5	1.9	6.8
WSW	3.0	2.4	9.8	15.9	2.8	2.1	6.7	3.1	2.2	9.1
W	2.9	2.5	16.7	23.5	2.7	2.1	11.7	3.0	2.1	13.9
WNW	3.3	2.6	16.7	20.6	3.6	2.5	15.0	3.6	2.5	13.1
NW	6.5	3.5	19.0	25.1	7.7	3.6	15.5	7.5	3.8	19.1
NNW	21.9	5.0	22.8	26.2	23.3	4.5	18.8	20.3	5.5	30.1
Calm	3.1				1.8			3.2		

[1)]Data from 1997, 1998, 2000, 2002, 2003, 2004, 2005, 2006, 2007, 2008 and 2009
*Data from 2011 are preliminary

during the winter months, the valley stations have much lower temperatures than the stations at higher elevations. This is mainly due to the effect of cold air sinking down and creating frequent inversions. From November 2010 to June 2011 M6 on top of Dombjerg only have sporadic measurements. Therefore data from December 2010 to May 2011 is not included in figure 2.4. Data from M7 in Store Sødal was not successfully retrieved until in April 2012.

Figure 2.3 Mean monthly air temperatures at Zackenberg during the period 1995-2011.



Winter hot spells (where the temperature suddenly rises above the freezing point) were registered at all stations except M6 (probably because of malfunctioning data logger). At the beginning of January 2011 one episode with temperatures up to three degrees celsius were registered at the climate stations, M3 and M7. Due to the limited access to M6 and the many problems arising at this station, the M6 on Dombjerg will be discontinued in 2012 and re-established on the mountain Zackenberg in 2013. This will ease the access and upgrading to CR1000 data loggers and will enable wireless data communication to the station in the future.

Snow depth

The amount of snow measured at the meteorological station during the winter 2010/2011 was below the average level. The build-up of a continuous snow cover above 0.1 m did not happen before the end of January 2011 (table 2.6). The maximum snow depth measured at the climate station was 40 cm, which was reached 26 April (figure 2.2 and figure 2.5). Snow melt started around 1 June and by 16 June the ground was free of snow below the sensor at the meteorological station (table 2.6). This is close to the average date for snow melt in the Zackenberg valley. The winter had a very short period with continuous snow cover above 0.1 m (135 days). This was close to the shortest period ever, 108 days during the winter 2008/2009 (table 2.6). The thin snow cover is reflected in the soil temperatures that were lower than during most previous winters (figure 2.5).

Snow depth is also being measured at the automatic weather stations M2, M3 and M7 (figure 2.6). Snow depth at both M3 and M7 peaked in the end of March while M2 and the climate station did not peak until the end of April. The build-up under M2 from 19 April to 20 April is properly due to strong wind with resulting snow drifting. By 16 June, snow had disappeared from all stations.

In order to achieve a better spatial resolution of snow depths for the modelling,

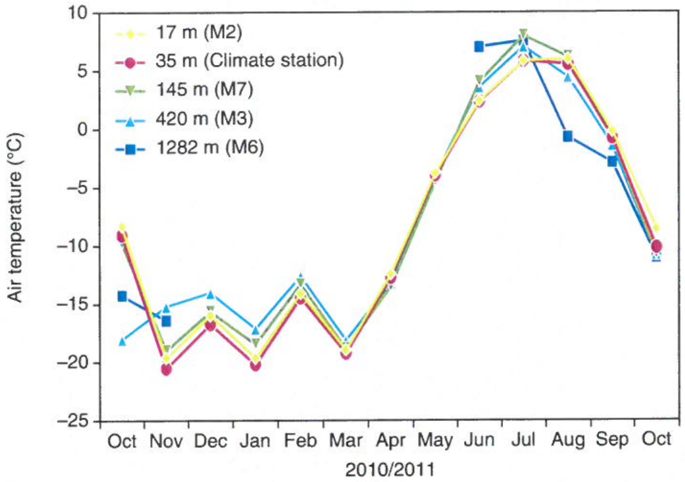


Figure 2.4 Mean monthly temperatures from automatic weather station M2 (17 m a.s.l.), M3 (420 m a.s.l.), M6 (1282 m a.s.l., M7 (145 m a.s.l.) and climate station (35 m a.s.l.) during the period 1 October 2010 to 30 October 2011.

Table 2.4 Climate parameters for June, July and August 2002 to 2011. [1] Wind velocity, max is the maximum of 10 minutes mean values.

Year	Month	Shortwave rad. (W m^{-2})		Net rad. (W m^{-2})	PAR (mmol m^{-2} s^{-1})	Air temperature (°C)			Precipitation (mm)	Wind velocity (m s^{-1})		Dominant wind dir.
		mean in	mean out	mean	mean	mean 2 m	min. 2 m	max. 2 m	total	mean 7.5 m	max[1] 7.5 m	7.5 m
2002	Jun	344	151	113	–	2.6	−2.8	14.9	1	1.6	6.8	SE
	Jul	205	23	105	424	5.7	−0.9	13.8	11	2.6	9.9	SE
	Aug	129	16	51	272	4.9	−3.1	11.6	15	2.8	12.9	SE
2003	Jun	294	108	106	612	2.2	−4.8	14.7	7	1.6	5.4	SE
	Jul	210	26	96	431	7.7	1.8	16.7	6	2.8	14.2	SE
	Aug	151	20	56	313	6.6	−0.5	15.4	3	2.5	10.1	SE
2004	Jun	279	73	111	571	2.5	−3.4	19.1	3	2.3	13.6	SE
	Jul	225	30	95	464	7.2	−0.7	19.0	10	2.8	10.5	SE
	Aug	150	20	62	302	5.6	−1.4	17.2	4	2.4	12.6	SE
2005	Jun	261	53	–	519	2.7	−3.5	13.4	6	2.4	11.8	SE
	Jul	215	29	–	428	6.9	−0.6	21.8	28	2.9	13.3	SE
	Aug	154	21	51	321	4.6	−2.7	14.0	4	3.2	10.9	SE
2006	Jun	312	208	54	675	1.0	−4.4	9.5	0	1.7	6.9	SE
	Jul	256	28	131	550	6.6	−1.2	22.8	12	2.5	11.3	SE
	Aug	158	21	61	336	5.5	−4.5	16.3	2	2.6	12.0	SE
2007	Jun	287	86	116	609	3.3	−2.4	15.8	9	2.2	14.8	SE
	Jul	251	32	118	531	5.9	−1.8	16.4	8	2.2	6.5	SE
	Aug	149	20	56	320	6.6	−2.6	13.6	6	2.7	12.3	SE
2008	Jun	284	145	74	612	5.2	−1.5	12.8	3	1.9	11.7	ESE
	Jul	260	32	126	551	8.8	0.0	18.4	8	2.8	14.2	SE
	Aug	141	19	51	296	8.0	0.3	17.1	49	3.3	16.9	SE
2009	Jun	257	32	134	532	1.9	−2.4	9.3	3	2.6	11.0	SE
	Jul[2]	233	30	103	487	7.9	0.4	18.1	26	3.3	15.4	SE
	Aug[2]	145	18	48	292	4.4	−1.8	11.6	31	2.8	24.4	SE
2010	Jun[2]	272	95	98	548	1.9	−8.1	12.8	13	2.0	10.2	SE
	Jul[2]	264	40	123	529	5.3	−1.7	15.1	1	2.6	15.7	SE
	Aug[2]	164	27	58	325	5.3	−2.6	16.1	2	2.6	15.0	SE
2011	Jun	300	84	122	590	2.3	−5.9	13.8	–	2.1	12.3	SE
	Jul	254	41	118	503	5.8	−0.8	14.5	–	2.4	15.0	SE
	Aug	147	23	61	–	5.6	−2.4	19.7	–	2.7	12.6	SE

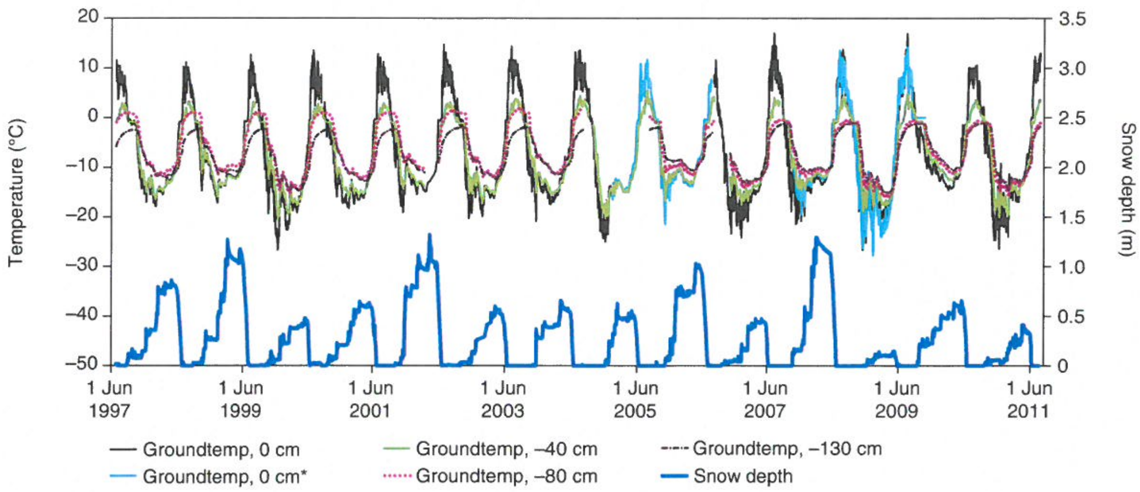


*Figure 2.5 Daily mean soil temperatures and snow depth from the meteorological station 1997–2011. In August 2006 soil temperature sensors were replaced. *Data from sensor at the snow depth station.*

Table 2.5 Positive degree-days calculated on a monthly basis as the sum of daily mean air temperature above 0 °C. Calculations are based on air temperatures from the meteorological station.

Degree days	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
January										1.5		3.6				
February																
March																
April								0.2	1.1		2.9					
May	1.1	1.3	0.1	3.6	0.5	0.5	18.2	3.3	4.1	5.4	3.1		10.0	12.3	0.4	0.6
June	63.7	74.6	32.5	52.9	71.8	68.2	81.8	74.2	73.9	84.6	37.2	99.7	155.0	64.6	73.3	78.1
July	181.0	115.4	147.4	192.7	164.4	152.0	175.6	237.2	222.2	214.7	205.3	182.2	270.8	265.6	165.6	180.1
August	140.5	154.2	143.6	89.2	127.3	181.2	152.5	203.2	169.4	141.5	171.5	204.5	213.7	141.3	164.3	172.5
September	15.3	4.5	11.3	19.7	5.7	31.1	41.2	42.5	41.4	17.7	15.7	10.1	63.1	8.9	29.6	18.7
October		1.5				0.3	1.8									
November																
December																
Sum	**401.7**	**351.5**	**334.8**	**358.0**	**369.7**	**433.2**	**471.1**	**560.6**	**514.8**	**466.4**	**435.7**	**500.1**	**712.6**	**492.7**	**433.2**	**450.1**

Table 2.6 Key figures describing the amount of snow at the meteorological station during the last 14 winters.

Winter	97/98	98/99	99/00	00/01	01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11
Max. snow depth (m)	0.90	1.30	0.50	0.70	1.30	0.60	0.70	0.70	1.10	0.60	1.30	0.18	0.66	0.45
Max. snow depth reached	29 Apr	11 Mar	19 May	25 Mar	15 Apr	13 Apr	13 Apr	12 Feb	26 Apr	4 May	6 ar	17 Feb	19 May	25 Apr
Snow depth exceeds 0.1 m from	19 Nov	27 Oct	1 Jan	16 Nov	19 Nov	6 Dec	24 Nov	27 Dec	19 Dec	12 Jan	26 Oct	29 Jan	25 Sep	26 Jan
Snow depth below 0.1 m from	25 Jun	3 Jul	14 Jun	24 Jun	20 Jun	14 Jun	13 Jun	7 Jun	1 Jul	8 Jun	24 Jun	16 May	16 Jun	10 Jun

snow depths are also being measured along two main transects, i.e. one transect (SNM) running from Lomsø into the Zackenberg valley and another (SNZ) running along the ZERO line from the old delta up to 420 m a.s.l. These snow depths will be used as input for the SnowModel covering the central part of the Zackenberg valley and possibly compared directly to normalized difference vegetation index (NDVI) and vegetation development along the ZERO line.

By mid-October 2011, the Zackenberg valley was more or less totally covered by new snow with a bulk density of 330 kg m-3. There was a lot of wind during and after the snowfall, which caused the relatively high density. The snow densities during the fall of 2011 were all relatively high compared to previous fall periods.

Snow cover

The snow cover depletion for 2011 was close to average for the 1995-2011 period (figure 2.7). Real change in snow cover started in early June with 50% snow cover occurring 15 June. In late June, the snow cover depleted fast ending up as in 2010 being one of the years where all snow within the area of the camera coverage disappeared earliest.

The snow cover 10 June, which has been chosen as a good early season indicator for biological conditions, is given for different sub-sections of the study area in table 2.7. Values for 2011 are close to average for the eastern most sections (9, 10 and 11) but significantly lower in the other sections compared to average for the period 1995-2010.

Active layer depth

Development of the active layer (the layer above the permafrost that thaws during the summer) starts when the air temperature becomes positive and snow has disappeared from the ground. The depth of soil thaw was measured throughout the field season at two grid-plots; ZEROCALM-1 (ZC-1) covering a 100×100 meter area with

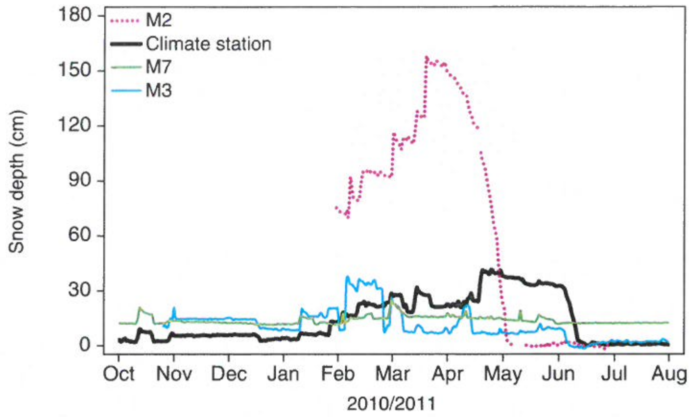


Figure 2.6 Snow depths at the automatic weather stations in 2010/2011, M2 (17 m a.s.l.), M3 (420 m a.s.l.), M7 (145 m a.s.l.) and the climate station (35 m a.s.l.).

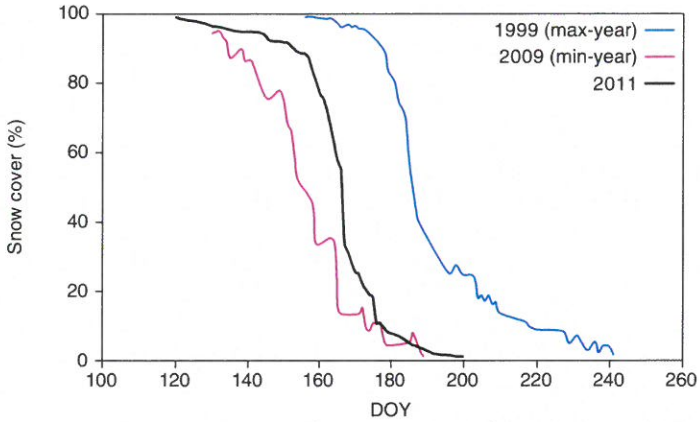


Figure 2.7 Snow cover depletion curves from the central part of the Zackenberg valley. The three years shown in the figure, is 2009 with a very early melt-off, 1999 with a late melt-off and the depletion curve for 2011. Curves exist from 1998-2011.

Table 2.7 Area size and snow cover 10 June in 13 bird and mammal study sections in the Zackenberg valley and on the slopes of Aucellabjerg 2001-2011 and mean for the period 1995-2010 (see figure 4.1 in Caning and Rasch 2003 for map of sections). Photos were taken from a fixed point 480 m a.s.l. on the east facing slope of the mountain Zackenberg within +/- 3 days of 10 June and extrapolated according to the methods described by Pedersen and Hinkler (2000). Furthermore, the proportions of the areas not visible from the photo point are given. Values in italic are based on only part of the given section due to missing photo coverage.

Section	Area (km²)	Area hidden (%)	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean (1995-2010)
1 (0-50 m)	3.52	3.5	73	77	68	48	31	74	38	62	*13*	53	53	61
2 (0-50 m)	7.97	1.2	87	87	92	49	25	81	43	77	*5*	61	50	68
3 (50-150 m)	3.52	0.0	89	82	83	51	35	77	40	74	11	48	32	65
4 (150-300 m)	2.62	0.0	79	56	73	39	28	65	36	54	19	32	23	53
5 (300-600 m)	2.17	0.0	56	36	49	16	25	62	25	46	17	12	15	39
6 (50-150 m)	2.15	75.3	84	78	74	56	50	*80*	*50*	*59*	*18*	*49*	*29*	66
7 (150-300 m)	3.36	69.3	84	74	90	56	46	*82*	*58*	*69*	*34*	*44*	*27*	68
8 (300-600 m)	4.56	27.5	45	52	66	30	29	*67*	*26*	*45*	*16*	*25*	*11*	45
9 (0-50 m)	5.01	6.2	96	96	100	58	23	73	49	80	*18*	56	72	73
10 (50-150 m)	3.84	2.9	97	93	100	56	47	92	57	85	43	55	80	78
11 (150-300 m)	3.18	0.2	97	88	100	66	61	88	54	73	77	51	79	79
12 (300-600 m)	3.82	0.0	73	65	98	53	70	85	38	53	64	43	50	65
13 (Lemmings)	2.05	1.0	83	83	89	46	25	79	41	73	4	64	54	65
Total area	**45.70**	**12.9**	**82**	**77**	**83**	**49**	**37**	**77**	**43**	**65**	**28**	**44**	**46**	**64**

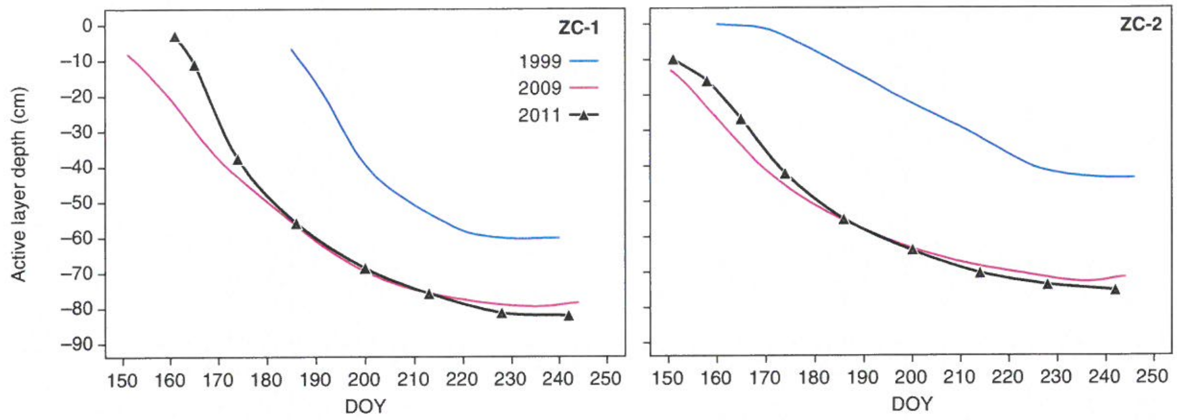


Figure 2.8 Thaw depth progression in ZEROCALM-1 and ZEROCALM-2 during summer 2011 (bold black line). Minimum and maximum thaw years (1999 and 2009, respectively) are shown as blue and red lines, respectively.

Table 2.8. Average maximum thaw depth (in cm) for grid points in ZEROCALM-1 and ZEROCALM-2 measured late August, 1997-2011.

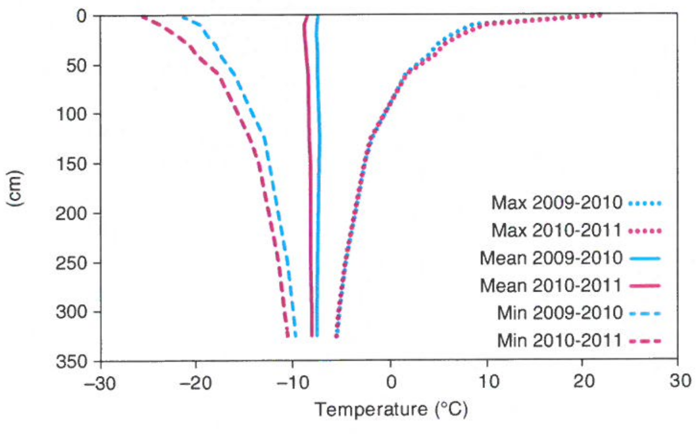
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
ZEROCALM-1	61.7	65.6	60.3	63.4	63.3	70.5	72.5	76.3	79.4	76.0	74.8	79.4	79.4	78.2	82.0
ZEROCALM-2	57.4	59.5	43.6	59.8	59.7	59.6	63.4	65.0	68.6	67.6	67.1	67.5	72.9	69.5	75.3

121 grid nodes and ZEROCALM-2 (ZC-2) covering a 120×150 meter area with 208 grid nodes.

In ZC-1, the first grid node was free of snow 7 June and within ten days all snow in this relatively homogenous grid site had melted. The maximum thaw depth was reached by the end of August and was deeper than previous maximum thaw depths measured at these grids (figure 2.8 and table 2.8).

In ZC-2, there were five grid nodes without snow cover 6 May and by 23 June all grid nodes were free of snow. The maximum thaw depth was reached at the end of August/early September and for this plot it was close to the deepest thaw that has been measured since 1997, even though the timing of the snow melt was average.

Figure 2.9 Minimum, mean and maximum temperatures from the borehole at M4. 30 October 2009 to 29 October 2010 (purple) and 30 October 2010 to 29 October 2011 (blue).



Data from the two ZEROCALM-sites are reported to the circumpolar monitoring programme CALM III (Circumpolar Active Layer Monitoring-Network 2009-2014) maintained by Centre for International Studies, the University of Delaware (www.udel.edu/Geography/calm).

Temperature in different settings and altitudes

GeoBasis operates several mini data loggers for year-round temperature monitoring in different altitudes and different geomorphologic settings in the landscape. Positions and a short description of the sites are given in the GeoBasis manual.

Year-round soil temperatures in the active layer are being logged at the meteorological station, at the automatic weather stations M2, M3, M4 and M5 and at the automatic chamber site in the fen (figure 2.1). At M4 a 325 cm deep borehole monitors temperatures from the upper part of the permafrost (Jensen and Rasch 2009). Now three years of data has been obtained from this borehole (figure 2.9). In 2012, we hope to be able to establish a deeper borehole to obtain more knowledge of the state of the permafrost in the Arctic. For Greenland there is a gap within data from boreholes and it would be very valuable to include a 10-20 m deep borehole with temperature loggers as part of the Zackenberg long-term monitoring programme.

Lake drainage

Photos from the digital camera at the A.P. Olsen Land glacier dammed lake was retrieved 6 May 2011. The camera was installed in April 2008 to cover fluctuations of the glacier dammed lake (figure 2.10). Daily photos had been obtained since 10 May 2008 except from a gap between October 2009 and May 2010 because of a full memory card. The photos (figure 2.10) show how the lake builds up from a minimum in spring 2010 to a maximum during late summer and fall, new ice covered the lake from 20 September. Unlike 2009 the lake did not drain in the summer 2010. In January 2011, the lake is completely covered with ice and snow patches. From 1 February to 10 March the camera was unfortunately covered by snow. The picture from 12 March shows the lake drained completely through the glacier. Ice on the banks along the river Zackenberg was observed when personnel arrived at the station in late April, which is evidence of the outburst from the glacier lake in March. From the hydrometric station and the ca-meras covering the Zackenberg valley it was clear that the water arrived in the lower part of the valley 8 March. The distance from the lake to the hydrometric station is approximately 35 km. Depending on the seasonal timing

Figure 2.10 Glacier dammed lake at A.P. Olsen Land. The lake builds up during the summer 2010 and is covered by ice in January 2011 before it drains early in March 2011. Then the lake builds up again and drains 22 July 2011. Photos: GeoBasis programme.

for the outburst severe erosion can take place along the river banks. If it happens during winter (as in 2008) when the landscape is covered by ice and snow the erosion is minimal whereas if it happens during summer (as in 2009) when the riverbanks are free of snow and the soil has thawed the erosion impact may be very large.

During the 2011 summer field season another flood from the glacier dammed lake at A.P. Olsen Land was observed at Zackenberg 22 July.

2.3 River water discharge and sediment transport

The river Zackenberg

The drainage basin of the river Zackenberg includes the Zackenberg valley, Store Sødal, Lindemansdalen and Slettedalen. The basin covers an area of approximately 514 km^2 of which 106 km^2 are covered by glaciers. The first hydrometric station was established in 1995 on the western riverbank near the river mouth (Meltofte and Thing 1996). In 1998, the hydrometric station was moved to the eastern bank of the river, due to problems with the station being buried beneath a thick snowdrift each winter. During the years, the station has been flushed away a few times by the major floods from the ice dammed lake at the A.P. Olsen Land. The present position on the eastern river bank near the river crossing site is not perfect since large boulders at the river bottom creates some rather big waves during high flow. However, by combining different methods to decide water level fluctuations reliable data are obtained.

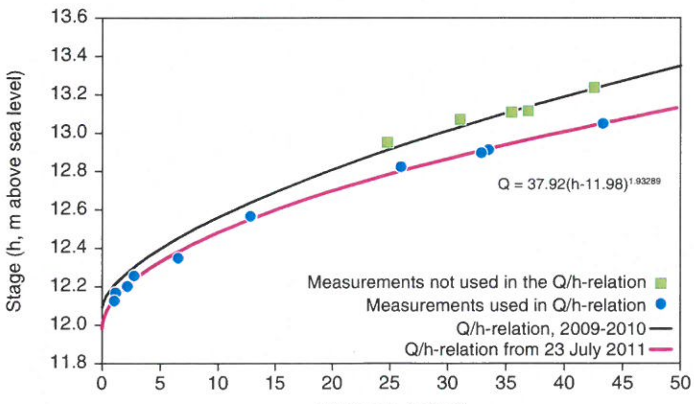


Figure 2.11 Stage-discharge relations (Q/h-relation) for the river Zackenberg at the hydrometric station. Purple line – relation valid from 23 July 2011, green line – relation valid before 23 July 2011 (=Q/h-relation, 2009-2010). The coefficient of correlation (R2) for the new relation is 0.986.

At the station, water level, water temperature, air temperature and conductivity are logged automatically every 15 minutes. In 2011, the water level was measured with a sonic range sensor and different pressure transducers.

Q/h-relation

After a large flood in 2005, the river cross profile changed and a new Q/h-relation had to be established. The new relation was valid until the end of the 2006 season. Unfortunately, the changed river cross profile made safe manual discharge measurements at high water levels almost impossible. This was the main reasons for the Danish Environmental Protection Agency to donate an Acoustic Doppler Current Profiler (ADCP) of the type Q-liner, which has now been used with great success since 2009. For further description, see Jensen and Rasch 2011. As the major floods make the river profile unstable a new Q/h-relations has to be established almost every year.

In 2011, twenty-nine discharge measurements were carried out. Of these, nineteen measurements were carried out under snow and ice-free conditions where the Q/h-relation is valid. In July another flood occurred, which again changed the river profile. Therefore, a new Q/h-relation has been established. The new Q/h-relation is based on 10 measurements and is valid from 23 July 2011 (figure 2.11).

River water discharge

Water passed the station 8 May 2011, when water that was dammed in Store Sødal after an outburst flood from the ice dammed lake at A.P. Olsen Land in March, made its way on top of the snow packed river bed. Water from Lindeman and other streams were significant contributors from the end of May. There was another flood 22 July, which is registered at the hydrometric station (figure 2.12).

The water discharge from 2011 is shown in figure 2.12. From the river started flowing and until 22 June the riverbed and banks were covered with ice and/or snow to such a degree that the Q/h-relation was invalid. Instead, the discharge is approximated by interpolation between 10 manual discharge measurements made during the period 11 June to 16 June. From 18 June until the Q/h-relation is valid the discharge is calculated by using a new method that was developed in 2010, see Larsen et al.

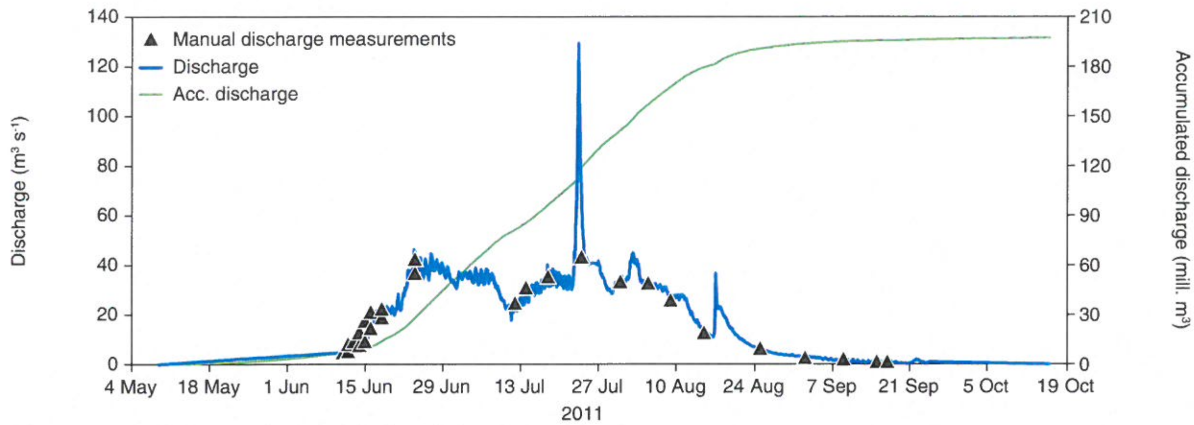


Figure 2.12 Water discharge in the river Zackenberg during 2011.

2011. From 22 June to 24 September, the discharge is calculated from the Q/h-relation (figure 2.11). After 24 September, the discharge is estimated to decrease linearly to an assumed zero discharge 15 October.

The total amount of water drained from the catchment area during the measuring period in 2011 was 197 million m^3. Despite the flood 22-23 July this is only slightly above the average discharge season, which is 188 million m^3 (table 2.9). The water level at the peak flood was lower than earlier seen, which probably is due to the fact that a minor outburst flood from the glacier occurred in March and that the lake at A.P. Olsen Land had not filled up to maximum level before draining again.

The peaks in the discharge all seems to be correlated with higher temperatures in the more elevated areas of the drainage basin and likewise the significant drop in discharge observed arround 1 August correlates with a drop in temperature in these areas (figure 2.13a and b). The slight increase in the end of August is a response to the rain event 17 August. This is also reflected as a peak in the conductivity. From mid-September, ice starts to form on the river and by 3 October, it is possible to cross the ri-ver on the ice. However, some water is still running below the ice – observed as late as 16 October.

Suspended sediment and river water chemistry

Daily water samples were collected in the morning (8:00) and in the evening (20:00) in order to determine suspended sediment

*Table 2.9 Total discharges in the river Zackenberg during the years 1996-2011, corresponding water loss for the drainage area (514 km²), and precipitation measured at the meteorological station and estimated suspended sediment transport. ¹⁾The hydrological year is set to 1 October previous year to 30 September present year. *)For 2005, no data is available during the flood from 25 July 05:00 until 28 July 00:00. After this date and until the new hydrometric station was set up on 5 August the discharge are estimated from manual readings of the water level from the gauge. **)No precipitation data available from 22 January to 7 April. No total precipitation as there is too many missing values.*

Hydrological year¹⁾	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Total discharge (mill m³)	132	188	232	181	150	137	338	189	212	>185*	172	183	201	146	173	197
Water loss (mm)	257	366	451	352	292	267	658	368	412	>360	335	356	391	284	337	383
Precipitation (mm)	239	263	255	227	171	240	156	184	279	266	206	133	219	157	>125**	–
Total annual transport																
Suspended sediment (ton)		29444	130133	18716	16129	16883	60079	18229	21860	71319	27214	51118	39039	44716	23538	38337
River break-up	late May	4 Jun	10 Jun	9 Jun	8 Jun	8 Jun	4 Jun	30 May	1 Jun	3 Jun	12 Jun	2 Jun	7 Jun	22 May	30 May	23 May

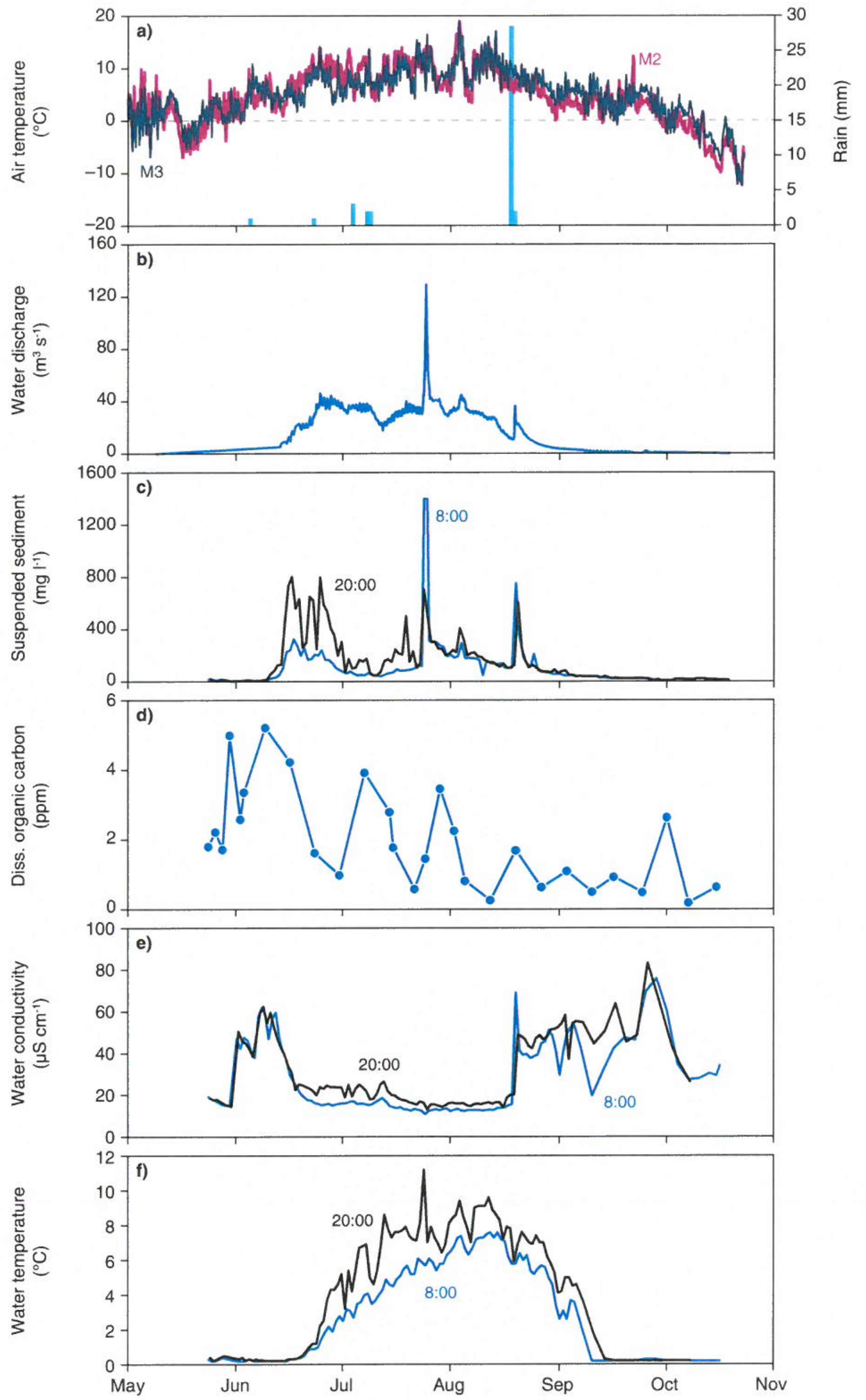


Figure 2.13 a) Diurnal mean air temperatures for 2011 at M2 (17 m a.s.l.) and at M3 (420 m a.s.l.) and rain registered at the meteorological station. Seasonal variations of selected parameters in the river Zackenberg: b) water discharge. c) suspended sediment concentrations at 08:00 and 20:00. d) dissolved organic content. e) conductivity at 08:00 and 20:00. f) water temperature at 08:00 and 20:00.

concentrations (SSC). As shown in figure 2.13c, SSC shows highest concentrations early in the season. At the same discharge rates, concentrations of suspended sediment are much lower in late July and August than in the first part of the summer – probably due to depletion of easy erodible material along the riverbanks. A distinct diurnal variation is measured early in the season whereas no variation is measured later during the season. This correlates with diurnal discharge variations being more distinct early in the season (figure 2.13b). Usually, the SSC are highest and show larger fluctuations in the afternoon and evening than in the morning.

The highest concentration of SSC during 2011 was 2288 mg l^{-1}, which was measured in the morning 23 July as a single peak value during the flood. The summer river burst began in the evening 22 July and ended the next day.

During the entire run-off period, the suspended sediment transport amounted to 38337 tonnes (table 2.9). In order to compare values between years, the total amount of sediment given is based solely on the SSC measured in the morning, but includes measurements carried out during flood events. If evening values were included, the total transport in 2011 would amount to 48112 tonnes. This indicates that all the calculated sediment yields given in the table are underestimated.

Daily variations of conductivity and water temperature are shown in figure 2.13d and 2.13e. The very first melt water early in the season shows high conductivity; a well-known phenomenon ascribed to solutes being washed out of the snow (Rasch et al. 2000). During the dry summer, the conductivity was very stable. The conductivity increases after a big rain event 17 August, where over 500 ml of rain was collected from the open bucket collector on the heath. The conductivity in the river peaks during rainy periods due to increased surface and subsurface drainage from land and soil water that has higher conductivity than melt water from the glacier.

Throughout the entire season, samples from the river were collected for mercury analysis. Results from this work are reported separately in section 6.2.

Suspended sediment and water discharge in Lindemanselven

Fluctuations of water level was measured in Lindemanselven approximately 300 m upstream from the junction between the rivers from Lindeman and Store Sødal (UTM: 511662 E, 8269094 N, 82 m a.s.l.). A logger with a pressure transducer was installed 22 July. This is later than previous years. Data was logged continuously every 15 minutes until mid-August. On 27 August, the pressure transducer was found underneath 31 cm sand and gravel. The big rain event 17 August apparently caused a lot of sediment from the hills to be washed out in Lindemanselven. Unfortunately, the pressure sensor failed and data from 17 August to the end of the season cannot be used. There is only water level data from 22 July until 17 August. The logger was removed 19 September due to ice formation.

The Lindeman discharge measurements will not be continued in the coming years.

2.4 Precipitation and soil water chemistry

Precipitation

Rain samples for chemical analyses were collected from an open bucket collector 3 July, 17 August and 22 September. Furthermore, snow samples were collected from a snow pit 22 September, 2, 10, 15 and 24 October. All precipitation samples were analysed for chemical composition.

Soil moisture and soil water

Variation in soil moisture content is measured at several sites. During the field season, soil moisture was measured once a week at all soil water sites and along two transects in ZEROCALM-2 (the active layer grid site). Besides the manual measurements, soil moisture is monitored continuously at the three automatic weather stations M2, M3 and M4 (figure 2.14). M2 is located on a slope and affected by large snow accumulation but dries out quickly due to the primarily sandy material. M3 is located on a gentle slope at 420 m a.s.l. and during the early summer, this site is affected by flow of melt water from snow patches further up the mountain. Finally, M4 is located in the *Cassiope* heath just north of the meteorological station.

Except from an increase around 6 June due to a wet snow event a steady drying of the soil is observed until 17 August where a rain event increased the soil moisture content. Soil freeze in the upper part of the active layer happened almost momentarily around 6 September at all three plots whereas it happens more gradually deeper in the soil as it is not directly exposed to the air temperatures. There was a wet event at 21 September where all stations rose in moisture levels. By mid-October most of the active layer was frozen at the sites.

Three to four times during the season, soil water was collected from various depths in the active layer at three different sites covered by *Cassiope* heath, *Salix arctica*, and mixed heath vegetation, respectively. In late August a new soil water site close to the automatic chambers where installed. At this new site four lysimeters/

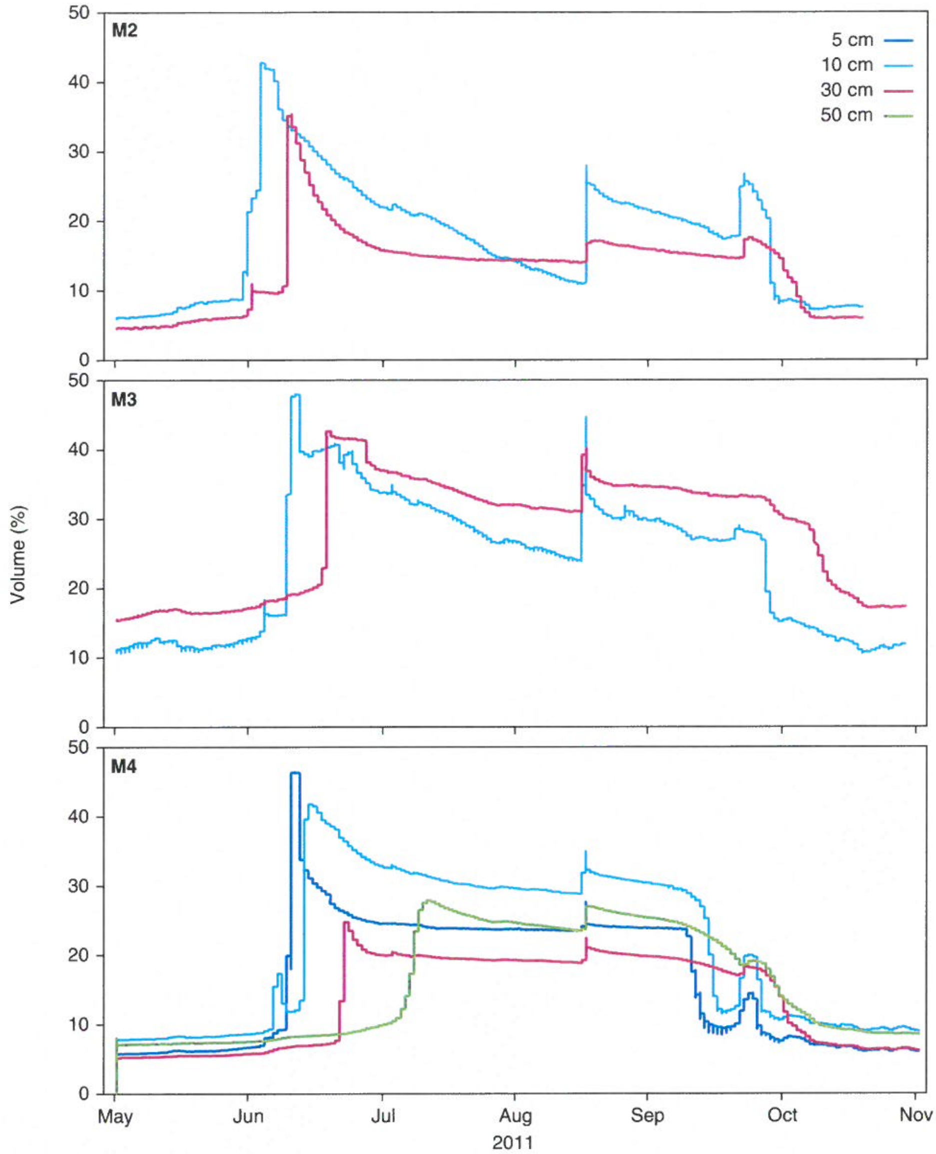


Figure 2.14 Soil moisture content throughout the field season 2011 at the three automatic weather stations M2, M3 and M4.

suction probes was installed in 10, 20, 30 and 50 cm depths. Collection from this site will start in 2012. The collected water from the other sites has been analysed for chemical composition.

2.5 Gas fluxes

Carbon gas fluxes are monitored on plot and landscape scale in the Zackenberg valley using two measurement techniques:

- Automatic chamber measurements of CH_4 and CO_2 exchange on plot scale in a fen site
- Eddy covariance measurements of CO_2 and H_2O exchange on landscape scale in heath and fen sites

Automatic chamber measurements

The CH_4 exchange has been monitored in six automatic chambers in a wet fen area since 2006 (Klitgaard et al. 2007). During 2011, the automatic chamber system was expanded to include two new chambers, giving eight chambers.

The temporal variation in CH_4 production is mainly associated with temperature, water table depth and substrate quality and availability. It has also been found from this site that frost action resulting in accumulated CH_4 gas squeezing out from the soil matrix can be of high importance for the annual CH_4 exchange (Mastepanov et al. 2008).

In 2011, measurements began 27 June and lasted until 31 October. Unfortunately, there were several leakage issues, especial-

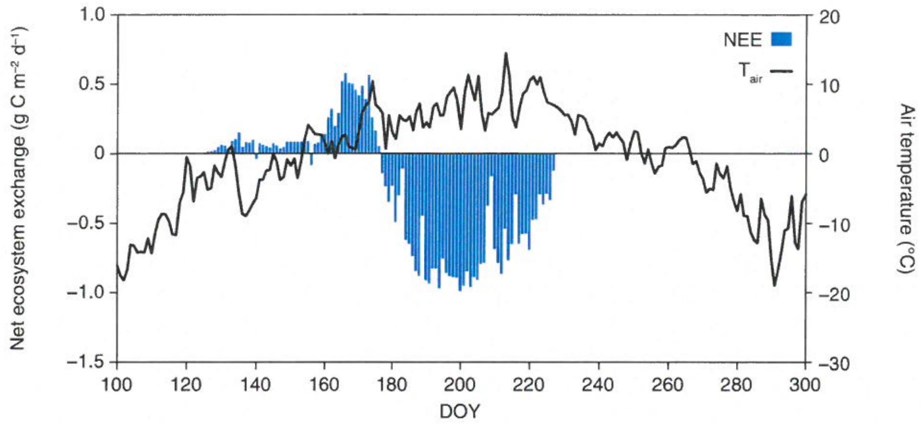


Figure 2.15 Daily net ecosystem exchange (NEE) and air temperature (T_{air}) measured at the heath site in 2011.

ly during the first weeks of measurements, resulting in less reliable data. As these issues need to be studied in more detail to ensure high data quality, figures on the CH_4 flux from the fen during 2011 cannot be published yet. However, some information on the CH_4 dynamics during 2011 can be given: Similar to previous years, there was an increase in CH_4 emissions during the early part of the growing season. During late August through September, fluxes were low and stable. In mid-October, there was an increase in both mean fluxes and variability between chambers, with a pattern similar to those observed in some of the previous years, most likely related to frost action releasing CH_4 stored in the soil profile. There is also an overall tendency, the flux magnitudes were lower during 2011 compared with previous years.

Eddy covariance measurements

The land-atmosphere exchange of CO_2 is measured using the eddy covariance technique at two sites in Zackenberg: One located in a *Cassiope* heath site where measurements have been conducted since 2000, and one located in a wet fen area where measurements have been conducted since 2007. Both eddy covariance systems consist of a 3D sonic anemometer and a closed-path infrared CO_2 and H_2O gas analyser. For further details of the instrumentation, see Klitgaard and Rasch 2008, and Rasch and Caning 2003. Raw data from the eddy covariance systems were calculated using the software package EdiRe (Robert Clement, University of Edinburgh). For more details on the flux calculation procedures see Jensen and Rasch 2010.

During August 2011, several changes were made to both the heath and the fen measurement systems, due to the EU-INTERACT project that has funded new sensors, which increase the coverage of energy flux components. In addition, the fen site has been upgraded to a so-called ICOS (Integrated Carbon Observation System) level 2 site, with new sonic anemometer (Gill HS) and CO_2 and H_2O gas analyzer (enclosed path LI-7200). The old setup at the fen site was running in parallel with the new system during fall and early winter, and in this report, only data from the old system is presented, as new data has not yet been processed.

The temporal variation in the mean daily net ecosystem exchange of CO_2 (NEE) and air temperature during 2011 for the heath and fen sites is shown in figures 2.15 and 2.16 and tables 2.10 and 2.11. NEE refers to the sum of all CO_2 exchange processes; including photosynthetic CO_2 uptake by plants, plant respiration and microbial decomposition. The CO_2 exchange is controlled by climatic conditions, mainly temperature and photosynthetic active radiation (PAR), along with the amount of biomass and soil moisture content. The sign convention used in figures and tables is the standard for micrometeorological measurements; fluxes directed from the surface to the atmosphere are positive whereas fluxes directed from the atmosphere to the surface are negative.

Heath site

Eddy covariance CO_2 flux measurements at the heath site in 2011 were initiated 3 May and lasted until 16 August. During the days following 16 August, the setup was changed in relation to an EU-INTERACT project so that data was being logged on a data logger instead of a computer. Due to technical issues, data from new setup has not yet been processed. Between 3 May and 16 August, approximately 2 %

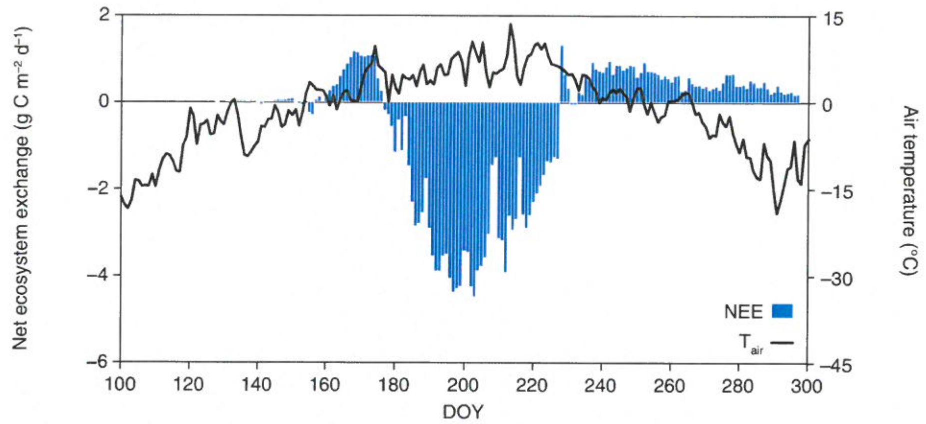


Figure 2.16 Daily net ecosystem exchange (NEE) and air temperature (T_{air}) measured at the fen site in 2011.

of the data were lost due to malfunction, maintenance and calibration.

The eddy covariance mast was placed on top of approximately 40 cm of snow and the snow cover in the fetch was 100 % when measurements started. Early season CO_2 fluxes were small; however, in the period between snow melt and start of net uptake period, CO_2 emissions increased and a maximum spring daily emission of 0.6 g C m^{-2} d^{-1} was detected 15 June. As the vegetation developed, the photosynthetic uptake of CO_2 started, and 26 June the heath ecosystem switched from being a source to a sink of atmospheric CO_2 on a daily basis.

The end of net CO_2 uptake period in the heath site was not included in the data set presented here. However, based on data from the fen site (see next section) it is likely that the last day with net CO_2 uptake was 15 August. By that assumption, the heath accumulated –31.5 g C m^{-2}, which is slightly more than the mean of all measurement years (–27.2 g C m^{-2}), during a net uptake period that lasted 50 days. It is mainly the onset of the uptake period that varies from year to year as it is regulated by the timing of snow melt, while the end of the period is more stable as it is governed by fading solar radiation. Maximum daily CO_2 uptake (–1.0 g C m^{-2} d^{-1}) measured 19 July, was however slightly less than mean of all years (–1.1 g C m^{-2} d^{-1}). During the entire measurement period (105 days) the net CO_2 balance amounted to –23.0 g C m^2.

In 2012, a scientific paper will be published based on the CO_2 flux measurements at the heath site (Lund et al. 2012 in press). It was found that temperature controlled the inter-annual variation in NEE, gross primary production (GPP) and ecosystem respiration (R_{eco}). However, while R_{eco} increased linearly with temperature, the initial increase in GPP with temperature levelled off at the high end of observed temperature range, suggesting that future increases in temperature may turn the heath ecosystem into a source for atmospheric CO_2.

Fen site

Eddy covariance CO_2 flux measurements at the fen site in 2011 began 7 May and lasted until 25 October. During this period, approximately 5 % of the data were lost due to malfunction, maintenance and calibration. During the first part of the measurement period until early June, fluxes were

*Table 2.10 Summary of the CO_2 exchanges 2000-2011 at the heath site. Please note that the measuring period varies from year to year. *Recalculated compared with earlier ZERO annual reports.*

Year	2000*	2001*	2002*	2003*	2004*	2005*	2006*	2007	2008	2009	2010	2011
Measurements start	6 Jun	8 Jun	3 Jun	6 Jun	3 Jun	21 May	28 May	27 May	30 Mar	16 May	5 May	3 May
Measurements end	25 Aug	27 Aug	27 Aug	30 Aug	28 Aug	25 Aug	27 Aug	28 Oct	28 Oct	22 Oct	31 Oct	16 Aug
Start of net uptake period	25 Jun	7 Jul	2 Jul	29 Jun	23 Jun	8 Jun	8 Jul	16 Jun	6 Jul	13 Jun	1 Jul	26 Jun
End of net uptake period	13 Aug	17 Aug	16 Aug	15 Aug	16 Aug	16 Aug	23 Aug	19 Aug	20 Aug	15 Aug	14 Aug	15 Aug
NEE for measuring period (g C m^{-2})	–18.8	–2.1	–5.4	–13.8	–13.2	–37.9	–24.9	–28.2	–11.2	–11.1	5.0	–23.0
NEE for net uptake period (g C m^{-2})	–23.2	–17.5	–16.6	–26.7	–24.6	–38.1	–28.9	–37.8	–32.0	–23.1	–26.8	–31.5
Max. daily accumulation (g C m^{-2} d^{-1})	–1.10	–1.10	–0.89	–1.26	–1.14	–1.40	–1.11	–1.32	–1.30	–0.97	–1.14	–0.97

Table 2.11 Summary of CO_2 exchanges 2007-2011 at the fen site. Please note that the measuring period varies from year to year.

Year	2007	2008	2009	2010	2011
Measurements start	20 Sep	10 Apr	31 Jul	9 May	7 May
Measurements end	19 Oct	30 Aug	13 Oct	1 Nov	25 Oct
Start of net uptake period	–	10 Jul	–	–	26 Jun
End of net uptake period	–	22 Aug	16 Aug	16 Aug	15 Aug
NEE for measuring period (g C m^{-2})	9.8	–65.8	3.5	–73.5	–80.5
NEE for net uptake period (g C m^{-2})	–	–94.6	–	–	–129.9
Max. daily accumulation (g C m^{-2} d^{-1})	–	–4.03	–	–5.15	–4.49

close to zero. As snow began to disappear in mid-June, fluxes increased and at 17 June, the highest daily emission during pre-growing season was measured (1.2 g C m^{-2} d^{-1}). The fen ecosystem switched from being a source for atmospheric CO_2 to a sink 26 June, and remained so until 15 August. During this period of net CO_2 uptake, 50 days, the fen accumulated –129.9 g C m^2. The highest daily CO_2 uptake was recorded 22 July, amounting to –4.5 g C m^2.

By 16 August, respiration processes exceeded the fading photosynthesis and the ecosystem returned to a net source of atmospheric CO_2. In the beginning of this period, there is plenty of fresh litter available and soil temperatures remain comparably high, allowing decomposition processes to continue at a decent rate. Autumn CO_2 emissions were approximately 1 g C m^{-2} d^{-1} until soil started to freeze in mid-September. Highest autumn daily emission was measured 16 August (1.3 g C m^{-2} d^{-1}). During the entire measurement period (172 days) the net CO_2 balance amounted to –80.5 g C m^2.

The growing season's daily uptake rates as well as shoulder seasons daily emissions are generally higher in the fen site compared to the heath site. This is because of denser vegetation with higher leaf area index in the fen site, allowing for higher CO_2 uptake per area unit.

2.6 Geomorphology

Coastal geomorphology

In 2008, the cliff top along the northern site of the active delta lobe was measured, while the shore-line was measured in 2010 and 2011.

The shore-line at the river delta showed a rapid decrease from 2008 towards 2010. Most of the protruding glacial cliff was eroded and a small island remained on the delta plain. From 2010 to 2011, the shore-line at the delta mouth was more stable. The cliff at the northern site of the delta retreated with some metres, while the beach west of the active delta plain showed an accretion in the same order of magnitude.

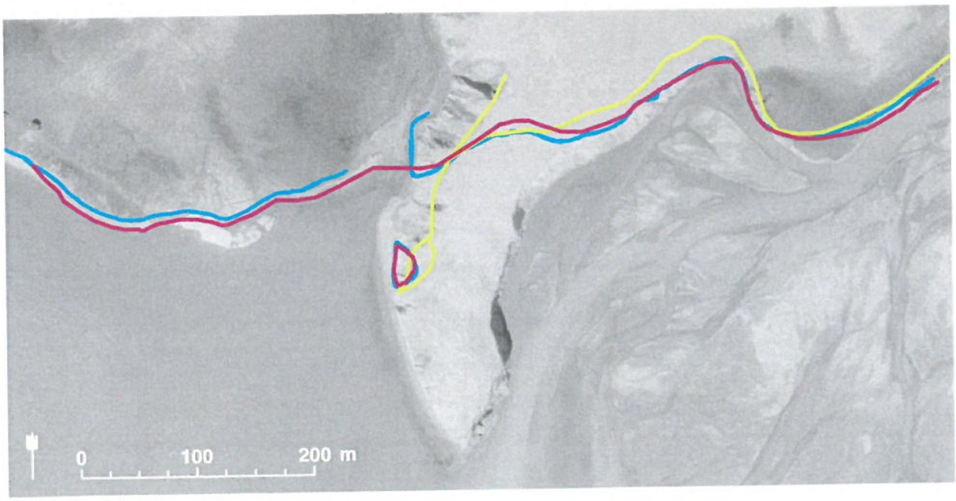


Figure 2.17 Delta and coastal cliff line measured by DGPS in 2008 (yellow line), 17 October 2010 (blue line) and 12 October 2011 (purple line) on an aerial photo from 8 August 2000.